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Geology of the Northeast Margin of the Salton Trough, Salton Sea, California

ABSTRACT

The San Andreas fault zone, in the Durmid area northeast of the Salton Sea, forms the northeast boundary of the Salton trough (the landward continuation of the Gulf of California rift). The zone is characterized by subparallel faults having both right-lateral and vertical separations. Stratigraphic offsets indicate at least 1,100 m of vertical separation on the San Andreas fault, southwest side downthrown, and [illegible]50-m right-lateral strike-slip separation is indicated by offset drainage.

An anticlinal structure southwest of the San Andreas fault is probably caused by drape folding over an upfaulted basement block or a recently intruded pluton. Small folds on the southwest flank of the anticline are caused by drag along the San Andreas fault and gravity sliding. An angular discordance of 18° between the Shavers Well and Borrego Formations indicates that folding adjacent to the San Andreas fault began prior to Borrego deposition in Pleistocene time. Folding followed deposition of the lacustrine Borrego Formation. Uplift halted, and the area was planed off by erosion. Renewed uplift followed, probably within the last few thousand years. *Key words: structural geology, stratigraphy, San Andreas fault, folds.*

INTRODUCTION AND GEOLOGIC SETTING

The Durmid area (Fig. 1) is an excellent location to study structural relations along the eastern margin of the Salton trough, a landward continuation of the Gulf of California rift. The Salton trough (Fig. 1), an isostatically compensated depression caused by thinning of the crust, contains a maximum sediment thickness of approximately 6,100 m, about 35 km east-southeast of Mexicali, Baja California (Biehler, 1964; Biehler and others, 1964, p. 132). From the deepest part of the trough, the irregular basement surface rises to crop out at San Gorgonio Pass (Fig. 1; Biehler and others, 1964, Fig. 6). Recent work suggests that the Gulf of California and the San Andreas fault are the result of sea-floor spreading and associated transform faulting (Menard, 1960; Hamilton, 1961; Harrison and Mathur, 1964; Rusnak and Fisher, 1964; Wilson, 1965; Larson and others, 1968).

The eastern margin of the Salton trough is characterized by a complex of subparallel branches of the San Andreas fault. The zone of faulting is about 8 to 16 km wide and extends from the north end of the Coachella Valley to the Durmid area northeast of the Salton Sea (Fig. 1). Its trace southeast of the Durmid area is commonly hidden by Pleistocene lake silts and dune sand. Evidence of active faulting can be seen, however, southeast of Niland, as offset cultural features and as lineaments on oblique infrared aerial photographs (Babcock, 1971).

The two major faults lying along the northeast border of the Coachella Valley are the Banning and Mission Creek faults. Southward in the Indio Hills, they join to become the principal fault of the San Andreas fault zone, which is parallel to the eastern shore of the Salton Sea (Fig. 1). Right-lateral displacements have been measured on faults of the San Andreas zone in the Indio Hills (Stotts, 1965) and Mecca Hills (Hays, 1957). The total right-lateral separation on the San Andreas fault in this area may be as much as 257 km (Crowell, 1962).

Relatively high seismicity characterizes the San Jacinto fault zone which enters the Salton trough through Borrego Valley west of the Salton Sea. Sharp (1967) documented about 24-km right-lateral separation on this fault. Other important faults of the San Andreas system in the Salton trough are the Imperial, Cucapa, Superstition Mountain, Superstition Hills, and Elsinore faults (Fig. 1).

The Mecca Hills lie immediately north of the Durmid area. Within the Mecca Hills, Cenozoic clastic rocks, tightly folded and cut by numerous closely spaced faults of the San Andreas system, form an anticlinorium. Crystalline basement rocks are exposed in Painted Canyon at the core of the anticlinorium (Hays, 1957, Pl. 2). This study indicates that the style of deformation in the Mecca Hills continues with little change southward into the Durmid area.

Previous Work

Little has been published about the geology of the Durmid area. Dibblee (1954) briefly described the sedimentary rocks and structure. He assigned the older coarse clastic rocks to the Palm Spring Formation and the younger lacustrine clay and silt to the Borrego lacustrine facies of the Palm Spring Formation and the unconformably overlying Brawley Formation. Dibblee's data for the Durmid area are summarized on the Salton Sea sheet (see Rogers, 1967).

STRATIGRAPHY

Sedimentary rocks within the Salton trough range in age from probable late Pliocene to Holocene. The sediments near the axis of the trough are deltaic sand, silt, and clay deposited by the Colorado River (Merriam and Bandy, 1965; Muffler and Doe, 1968). At the margins of the trough these fine-grained sediments interfinger with locally derived coarse-grained detritus.

Formations recognized within the Durmid area by the author include the lacustrine

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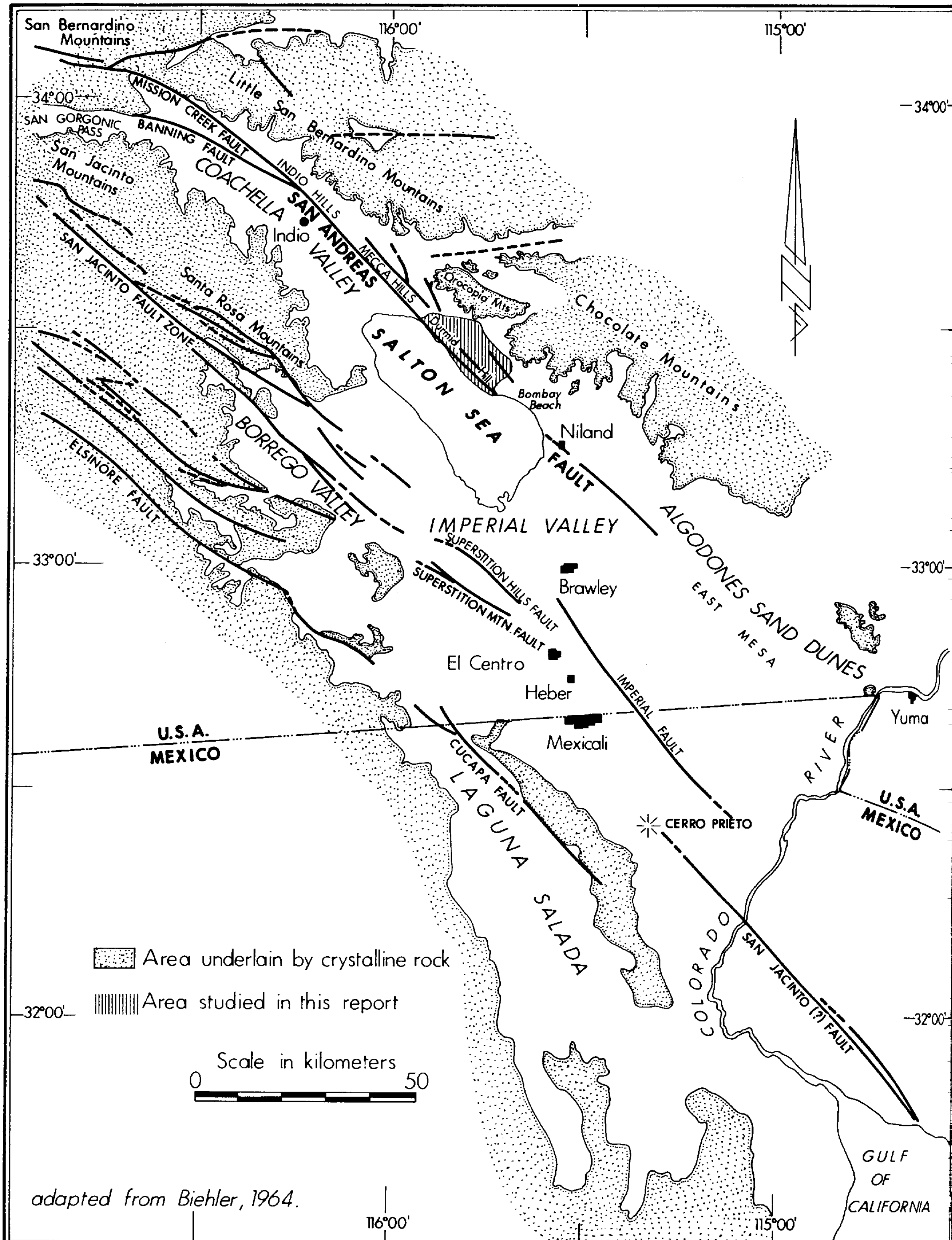


Figure 1. Index map of the Salton trough, California.

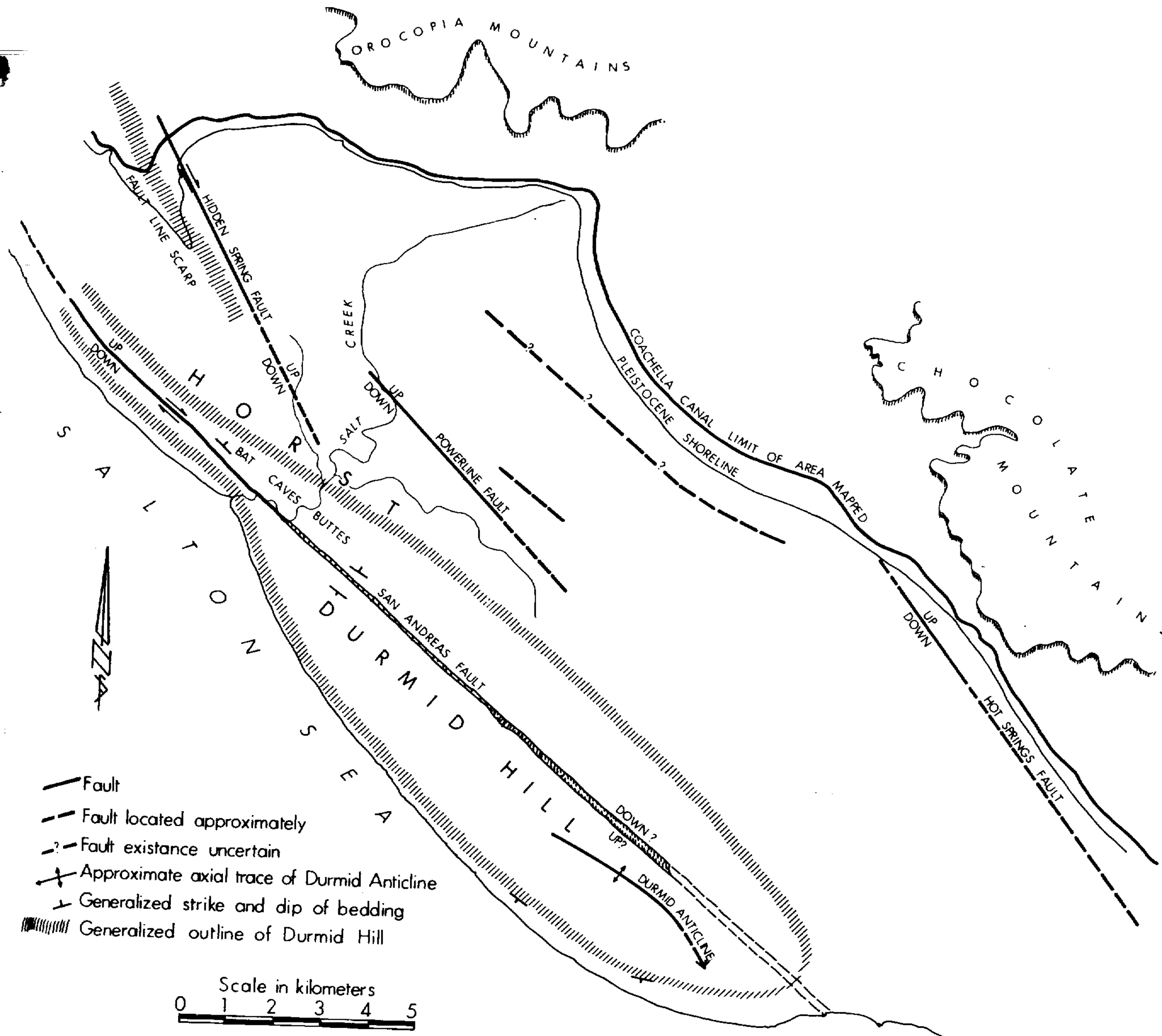


Figure 2. Sketch map of tectonic elements in the Durmid area.

Borrego Formation named by Tarbet and Holman (1944, p. 1781) and the coarse-grained Shavers Well Formation, defined by Hays (1957).

Shavers Well Formation

The Shavers Well Formation, of late Pliocene or early Pleistocene age, crops out northeast of the San Andreas fault at the Bat Caves Buttes (Figs. 2 and 5). The section exposed at the Bat Caves Buttes is approximately 765 m thick (Fig. 3); but the base of the formation is not exposed, and the upper surface is eroded. On the basis of lithologic similarities, the lower 550 m of the formation was assigned to the Sea View Member and the upper 215 m was assigned to the Skeleton Canyon Member of Hays (1957).

The lower 220 m of the Sea View Member is predominantly coarse-grained arkose and arkosic conglomerate, containing cobbles of coarse-grained plutonic rock derived from the eastern side of the Chocolate Mountains or from ranges east of the Orocopia Mountains (Fig. 1), where similar rocks are exposed today. Coarse-grained sandstone with interbeds of pebble conglomerate and siltstone make up the upper 330 m of the Sea View Member.

Finer grained than the Sea View Member, the Skeleton Canyon Member consists of medium- to coarse-grained sandstone in the lower half and mostly fine-grained sandstone and siltstone in the upper half of the member. Conglomerate beds in the top 15 m of the Shavers Well Formation contain pebbles of Orocopia schist which indicates uplift of the Orocopia Mountains, and possibly the Chocolate Mountains, when these sediments were being deposited.

Borrego Formation

The Borrego Formation crops out in the Durmid area between the San Andreas fault and the Salton Sea and on the plain northeast of Durmid Hill (Figs. 2 and 5). Exposed in the Durmid area is a 1,475-m-thick section which has been divided into six informal units (Fig. 4). Units 1 and 2, the lowermost, crop out near Salt Creek, northeast of the San Andreas fault; and units 3, 4, 5, and 6 crop out at the south end of Durmid Hill (Figs. 2 and 5). The complete Borrego section is not exposed in the Durmid area because the contact between units 2 and 3 is covered.

Based on faunal evidence, the Borrego Formation is a brackish water lacustrine deposit of Pleistocene age (Tarbet and Holman, 1944, p. 1782). Mineralogical analyses of samples of the Borrego Forma-

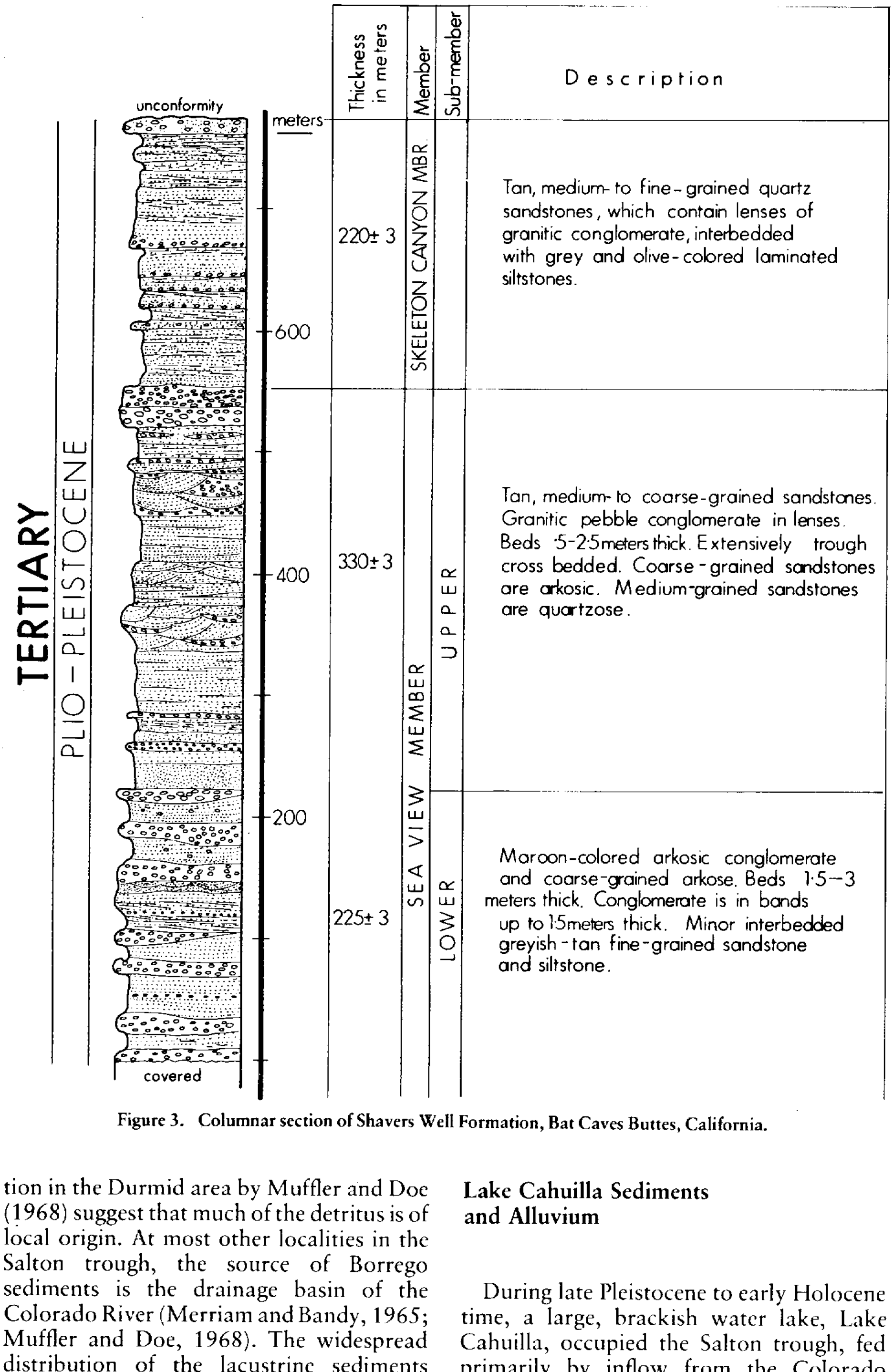


Figure 3. Columnar section of Shavers Well Formation, Bat Caves Buttes, California.

tion in the Durmid area by Muffler and Doe (1968) suggest that much of the detritus is of local origin. At most other localities in the Salton trough, the source of Borrego sediments is the drainage basin of the Colorado River (Merriam and Bandy, 1965; Muffler and Doe, 1968). The widespread distribution of the lacustrine sediments indicates deposition in a topographic depression similar to the modern Salton trough. The presence of thin evaporite layers interbedded with clay and silt, with uniform thickness for greater than 2,000 m along strike, indicates repeated dessication of the lacustrine basin during Borrego deposition. It also suggests that during Borrego deposition, subsidence of the basin occurred at approximately the same rate as deposition.

Lake Cahuilla Sediments and Alluvium

During late Pleistocene to early Holocene time, a large, brackish water lake, Lake Cahuilla, occupied the Salton trough, fed primarily by inflow from the Colorado River. Lake Cahuilla sediments crop out in the Durmid area as sheetlike deposits, such as the silt near Salt Creek; as shoreline deposits, such as spits and bars; and as isolated patches of sand and silt (Fig. 5). Composition of these sediments ranges from clayey silt to unlithified pebble conglomerate and generally reflects the composition of bedrock in the immediate vicinity.

Quaternary alluvium within the Durmid area consists of re-worked Lake Cahuilla sand and coarse, bouldery alluvium on the alluvial fans near the mountains.

Depositional History

Depositional events in the Durmid area are summarized below. During late Pliocene or early Pleistocene time, sediments carried into the area were mostly coarse clastics derived from ranges east of the Chocolate and Orocopia Mountains, indicating that these areas were exposed and shedding coarse detritus at that time. Near the end of Shavers Well deposition, uplift of the Orocopia Mountains is indicated by the presence of clasts of Orocopia schist in the Shavers Well Formation. Prior to deposition of the Borrego Formation, beds of the Shavers Well Formation were tilted and eroded, creating an erosional surface upon which the Borrego lacustrine sediments were deposited. During deposition of the Borrego Formation, the Salton trough probably had a configuration similar to that of today. The trough underwent repeated periods of dissication as shown by thin evaporite beds of considerable lateral extent. Dessication was interspersed with influxes of mostly clayey and silty sediments, largely derived from the Colorado River (Merriam and Bandy, 1965).

STRUCTURAL GEOLOGY

Major structural features of the Durmid area are illustrated in Figure 2; geologic features, in Figure 5. The San Andreas fault is the major structure in the area. Right-lateral separation of drainage and vertical separation (northeast side relatively upthrown) of approximately 1,000 m are observable along the fault. Vertical separations on the Hidden Spring and Powerline faults created a horst between these and the San Andreas fault. Other faults of the San Andreas system in the Durmid area have geomorphic expression, but their traces are hidden by Lake Cahuilla sediments and Quaternary alluvium. In some places, these sediments also cover the San Andreas fault.

The Durmid anticline lies southwest of the San Andreas fault near the south end of Durmid Hill. Geometrically complex, the fold is poorly defined, and its axial trace can only approximately be shown.

San Andreas Fault

The San Andreas fault zone is 30 m wide at Salt Creek, increasing to 150 m at the south end of Durmid Hill (Figs. 2 and 5). The zone is nearly vertical at Salt Creek where it consists of dark reddish-brown clayey gouge. Rocks within the zone at the south end of Durmid Hill are pervasively sheared and resemble sheared claystone of the Borrego Formation. Within this sheared clayey matrix are isolated sparse sandstone blocks with sheared margins, ranging in maximum dimension from a few centime-ers to 20 m (Fig. 6).

Right-lateral separation of Salt Creek by the San Andreas fault is 850 m. The creek has cut a meandering channel in the sheared Borrego Formation at the fault and does not make a sharp bend to join the fault trace. eparation of Salt Creek has occurred since deposition of the Borrego Formation in Pleistocene time. Brune (Wyss and Brune, 1968, p. 4692) calculated the rate of recent right-lateral slip for the entire Imperial Valley to be about 2.2 cm per yr. Had this slip occurred exclusively along the San Andreas fault, the separation of Salt Creek would have taken approximately 30,000 yr to occur. In historic time, however, the Imperial and San Jacinto faults have been the most active members of the San Andreas system in the Imperial Valley. Therefore, it is probable that during late Pleistocene time, much of the lateral slip in the Imperial Valley occurred along faults other than the San Andreas, and hence the offset of Salt Creek probably took considerably longer than 30,000 yr. Ash beds within the Borrego Formation might be datable and could thus establish a maximum possible age of aration of Salt Creek.

ertical stratigraphic separation across San Andreas fault is approximately 500 Salt Creek and 1,120 m at the south end Bat Caves Buttes, the northeast side of the fault having moved relatively upward. At Creek, and at the south end of Bat Caves Buttes, the Shavers Well and Borrego ations, juxtaposed across the San Andreas, strike nearly parallel to the fault, stratigraphic separation of the top of Shavers Well Formation approximates al fault separation. The amount of al separation cannot be estimated of Salt Creek and south of Bat Caves s because the rocks are covered by Lake illa sediments.

tical stratigraphic separations mea- across the San Andreas fault could explained by lateral slip; in this case, folded at an earlier time would have juxtaposed by large strike-slip move- to show apparent vertical slip. er, geomorphic evidence discussed n this paper, and the presence of e gravity and aeromagnetic lies between the San Andreas and n Spring and Powerline faults (Bab- 1969) suggest that vertical move- have been large.

ther Faults

trace of the Hidden Spring fault approximately 19 km northwest Salt Creek into the Mecca Hills (Figs. 2 The fault was mapped in the Mecca

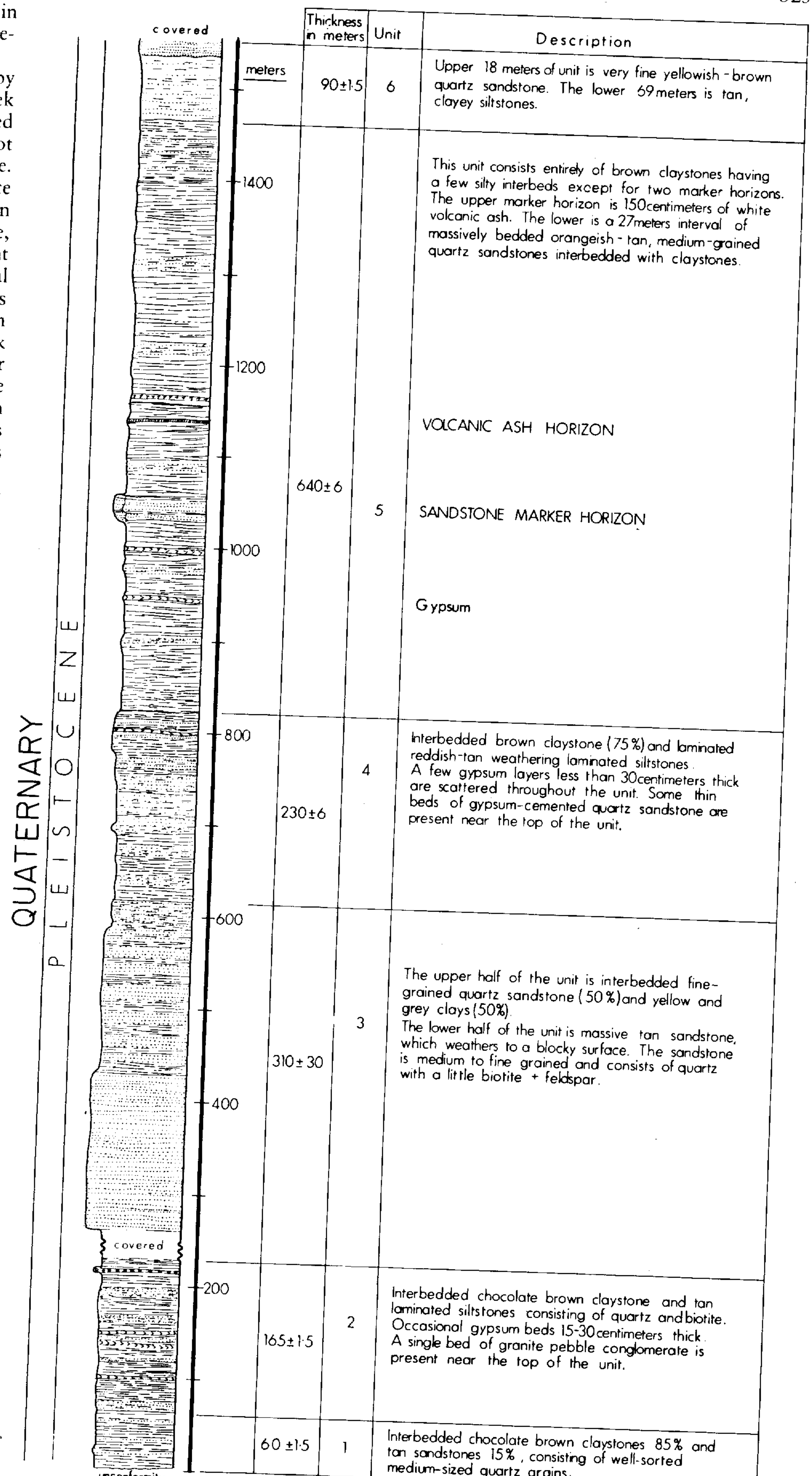


Figure 4. Columnar section of Borrego Formation east of Salton Sea, California.

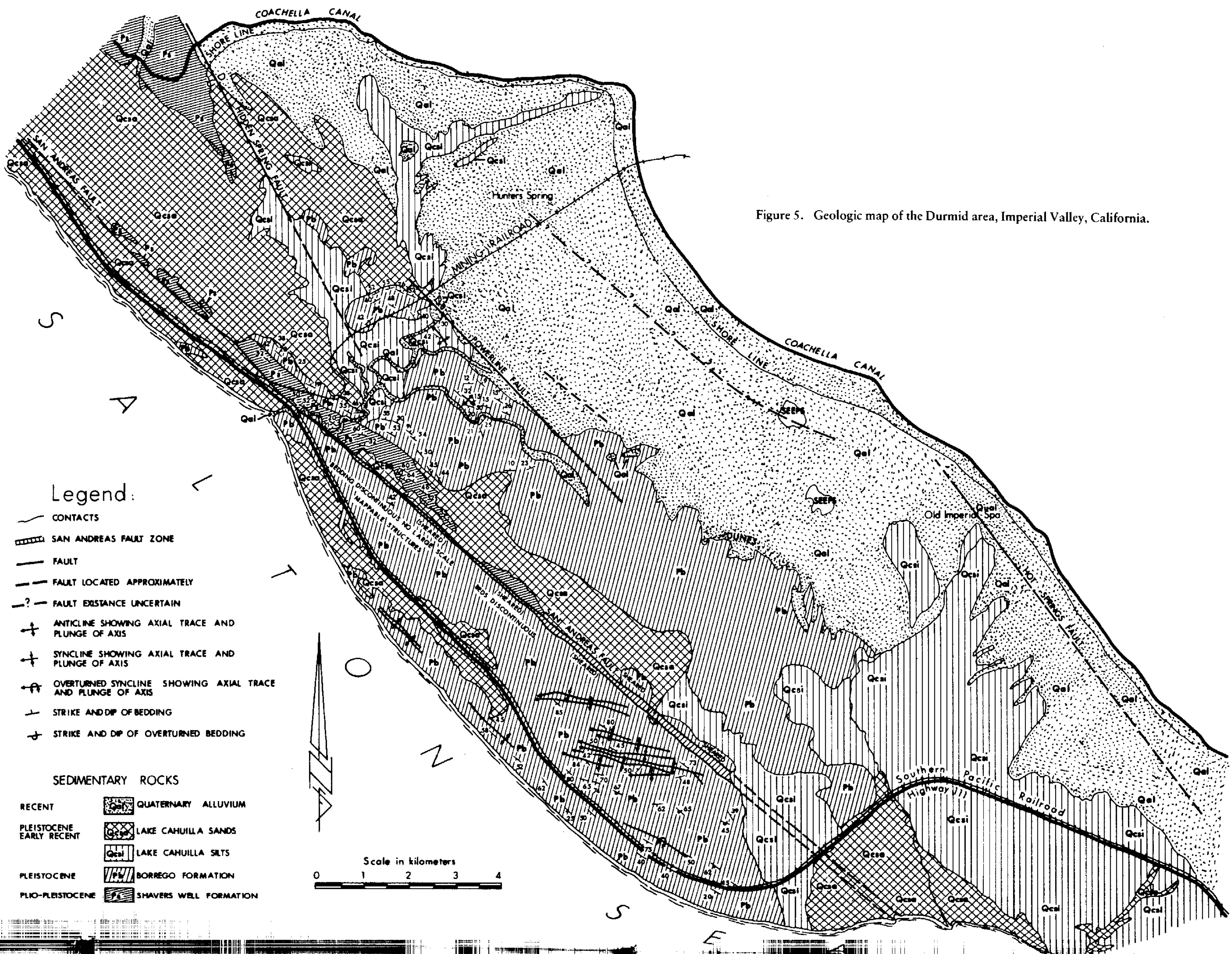


Figure 5. Geologic map of the Durmid area, Imperial Valley, California.

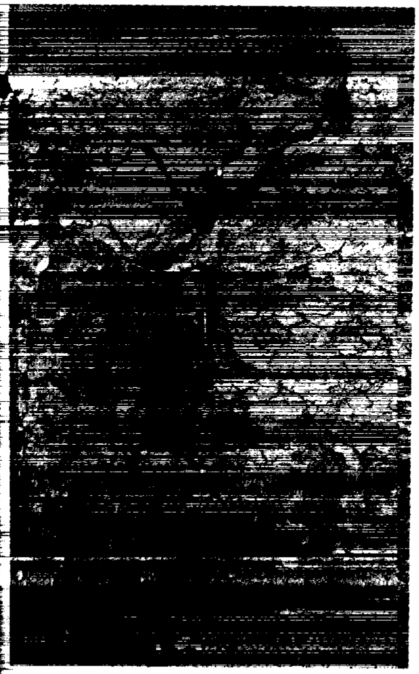


Figure 6. San Andreas fault zone 1.6 km northwest of the Bertram mine. An exotic block of sandstone is seen suspended in a matrix of sheared claystone of the Borrego Formation.

Hills by Hays (1957, p. 298), where it is a zone of gouge or breccia up to 10 cm thick. In the Durmid area, the fault trace is marked by a fault-line scarp near the Coachella Canal, and by springs occurring along a line from near the south end of the fault-line scarp to the Eagle Mountain Railroad tracks. Western margins of the springs are aligned, suggesting that the fault is located a few meters west of the springs and that the fault acts as a barrier to ground water flowing southwest away from the mountains. Nowhere is the fault surface visible. In Hidden Spring Canyon, in the southern Mecca Hills, Hays (1957, p. 300) found facies offsets suggesting 1,200 m of right-lateral separation, but found no indications of horizontal slip in the Durmid area. The apparent right-lateral offset of the Lake Cahuilla sand-silt contact (Fig. 5) is due to removal of the lake sand by erosion west of the fault and the exposure of the underlying silt. Hays (1957, p. 301) found dip-slip separation to be 75 to 105 m in Hidden Spring Canyon, the east wall having moved down. The fault-line scarp west of Hidden Spring fault in the Durmid area indicates the same sense of vertical separation. The horst between the Hidden Spring and San Andreas faults is a southerly continuation of the fault-bounded basement anticlinal structure mapped by Hays (1957) in the Mecca Hills.

The trace of the Hot Springs fault is hidden by bouldery alluvium, but its position is indicated by hot springs along a line between Frink Spring, southeast of the area mapped, and the Old Imperial Spa, and by drill data. The trend of the Hot Springs fault suggests that it is part of the San Andreas system. Drilling indicates the northeast side of the fault is upthrown (J. F. Mann, Jr., unpub. data).

A buried fault, roughly parallel to the San Andreas fault, extends southeast from Hunter's Spring to a prominent area of diffuse ground-water seeps about 8 km away (Fig. 5). On two gravity profiles trending perpendicular to the fault trace, the fault is marked by very sharp, narrow, positive gravity anomalies (Babcock, 1969, p. 61). The sense of displacement on this fault is not known.

The Powerline fault extends southeast 6.5 km from near the Eagle Mountain Railroad tracks (Figs. 2 and 5). Near the railroad, it lies on the northeast side of a line of springs in permeable sandy beds of lower units of the Borrego Formation. These beds are uplifted on the southwest side of the fault, whereas lake silt crops out on the downthrown northeast side of the fault. The Powerline fault coincides with the steepest gradients on the eastern side of a positive gravity ridge which underlies Durmid Hill, which also indicates that the southwest side of the fault is upthrown (Babcock, 1969, p. 63).

Unconformity between the Shavers Well and Borrego Formations

An angular discordance of about 18° between the Shavers Well and Borrego Formations indicates that uplift along the San Andreas fault and tilting of the sedimentary rocks northeast of the fault occurred prior to deposition of the Borrego Formation. The surface of unconformity appears to be unfolded on aerial photos. The unconformity is 500 m higher in the section at Salt Creek than at Bat Caves Buttes, an indication that the northeast side of the San Andreas fault has been uplifted more at Salt Creek than at the south end of the buttes. This agrees with stratigraphic separations observed across the fault.

Large Folds Associated with the San Andreas Fault

The Durmid anticline, a poorly defined anticlinal structure lacking a well-defined hinge line, is developed southwest of the San Andreas fault near the Bertram Mine (Babcock, 1969). Only the southwest limb and southeast-plunging nose of the fold are visible because the San Andreas fault cuts off the east limb. It is unlikely that a northeast limb is present opposite the southwest limb because of large lateral displacement on the San Andreas fault. The anticline makes up the southern 4 km of Durmid Hill and appears to die out to the northwest. Because of the many tight folds within the southwest limb of the anticline and the lack of a well-defined hinge, the fold is not apparent on geologic maps (Figs. 5 and 7), and the axial trace is only approximately located on Figure 2. However, the presence of the southeast-plunging anticlinal nose is indicated by an ash marker bed (Fig. 7). The anticlinal nature of the fold is also indicated by younger rocks exposed progressively farther from the core of the fold. The average dip of the southwest limb of the fold is 25° (Fig. 8); the fold plunges southeast the same amount.

Gravity and aeromagnetic data suggest the Durmid anticline is probably a drape fold caused by passive folding of the sedimentary cover over an upfaulted basement block or possibly a near-surface intrusive body similar to Obsidian Butte at the south end of Salton Sea (Babcock, 1969).

Near Bat Caves Buttes, the primary structures are two monoclines dipping away from the San Andreas fault on opposite sides of the fault. Near the fault, bedding dips about 55° NE. and flattens to approximately 9° at 1.5 km from the fault. Southwest of the fault, the Borrego Formation is highly contorted and poorly exposed. Younger beds of the Borrego Formation are exposed progressively farther from the fault, indicating predominant dip toward the southwest.

Small Folds

Small folds are developed in the Borrego Formation on the southwest limb of the Durmid anticline (Figs. 7 and 8). The folds die out near the shore of the Salton Sea, where, in most places, the rocks dip about 20° SW. These folds are of the passive flow variety, as defined by Donath and Parker (1964). Low in the Borrego section, near the San Andreas fault, the style of folding is nearly quasiflexural, but the folds retain enough characteristics of passive flow folding to be termed such. The folds range in length from less than 90 m to 1,500 m and are generally more open near the San Andreas fault than farther southwest near California Highway 111.

The sections shown in Figure 8 were interpreted from map geometry of folds because the folds cannot be seen in vertical section because of the flatness of Durmid Hill. The average dip of Durmid anticline, which controls the general configuration of the sections, was taken to be the minimum dip the ash marker bed could have and still maintain the measured stratigraphic thickness between the ash and siltstone marker beds; below this depth, folding presumably dies out. The dip of the major structure is only an approximation because unobserved tectonic thickness changes within the

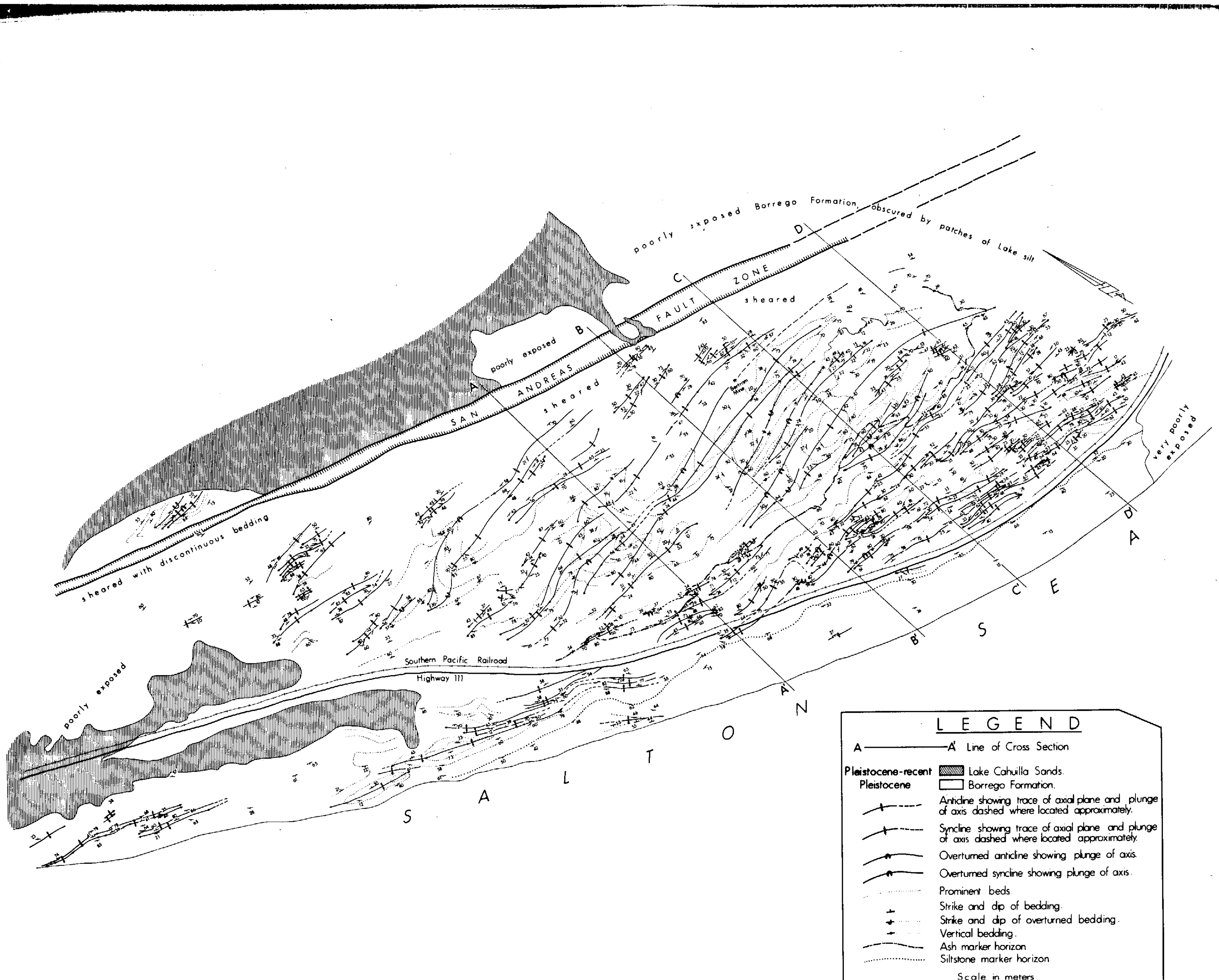


Figure 7. Geologic map of the south end of Durmid Hill, Imperial Valley, California.

Figure 7. Geologic map of the south end of Durmid Hill, Imperial Valley, California.

stratigraphic section between the ash and siltstone horizons may be possible.

High in the stratigraphic section, in a zone about 460 m wide, parallel to California 111 and west of the ash bed (Fig. 7), the flow folds are similar in style. The folds are tightly compressed, having high amplitudes relative to wave lengths. Most folds have wave lengths of about 60 m and axial length to wave length ratios of 15 to 20, with fairly uniform geometry along strike. The direction of tectonic transport is seen to be toward the southwest from observations of overturning and asymmetry of folds in that direction. Average dip of 66 axial surfaces of folds for the entire area of small folds is 55° NE.

The folds decrease in amplitude and increase in wave length lower in the section, closer to the San Andreas fault. In some of these folds, there appears to be little thinning of competent beds. However, no evidence of bedding-plane slip or other planes of décollement was observed, indicating that the dominant mechanism of folding was flowage. Most folds near the fault have wave lengths of 90 to 360 m. Fold axes are more nearly parallel, and the degree of asymmetry and overturning is less than in folds higher in the Borrego Formation.

Because the Shavers Well Formation is more competent than the Borrego Formation, the small-scale folds present at Durmid anticline may not extend into the underlying Shavers Well Formation, suggesting a surface or surfaces of slip between the formations. At Bat Caves Buttes, the steeply dipping Shavers Well Formation, near the San Andreas fault, contains no small folds.

Small-scale folding at Durmid anticline appears to belong to a single phase. The plunge of folds undulates slightly, but no cross folds are evident. The decrease in tightness of folds low in the Borrego Formation and close to the San Andreas fault cannot be fully explained because it is impossible to separate the effects of differences in lithology, depth of burial, and proximity to the fault. Folds in the more competent sandstone and siltstone low in the Borrego Formation would be expected to be more open and less overturned. They would also show less evidence of flowage than folds in the very ductile overlying claystone. However, differences in folds low in the section could be related to proximity to the San Andreas fault.

Possible Causes of Small-Scale Folding

Three possible mechanisms may have acted in concert to produce small-scale folding on the southwest flank of the Durmid anticline. The folding could have been caused by (1) post-Borrego regional compression in the Salton trough, (2) drag along the San Andreas fault, or (3) gravity sliding of the sedimentary cover off an upfaulted basement block or a rising intrusive body.

It is highly improbable that the folding was caused by regional compression within the Salton trough because no localities within the trough, except those associated with faults, exhibit folding similar to that at the Durmid anticline. Similar folding was described in association with faulting in the Indio Hills (Stotts, 1965) and Mecca Hills (Hays, 1957). Extensive areas of folded Borrego Formation, which might be the result of regional compression, are present in the Anza-Borrego desert centered about 15 km west of the Salton Sea. Within this area, however, the style of folding differs from that in the Durmid area. The dying out of the Durmid folded belt about 3,200 m from the San Andreas fault casts doubt on the hypothesis of regional compression and suggests that the small-scale folding is due to proximity to the San Andreas fault and the Durmid anticline.

Frictional drag acting parallel to a wrench fault can cause greater movement farther from the fault than close to it, which produces drag folds adjacent to the fault (Freund, 1965). The angle between these fold axes and the fault is small (0° to 15°) and increases away from the fault (Freund, 1965, p. 197). The folds are also tighter near the fault. This mechanism could produce those folds on the southwest limb of the Durmid anticline. However, two aspects of the folding do not fit the geometry predicted by Freund. First, the rocks farthest from the San Andreas are most tightly folded. Second, the folds farthest from the fault most nearly parallel the fault.

The third mechanism by which small-scale folding might have occurred is gravity sliding. The folded rocks are mostly claystone and lesser amounts of unconsolidated or semiconsolidated siltstone and sandstone. These rocks have low strength when dry. When wet, the claystone behaves plastically and should flow when subjected to a small differential stress. The upfaulting of a basement block or emplacement of an intrusive body beneath Durmid anticline could have provided the slope necessary for gravity sliding to occur. Gravity sliding could have been facilitated by possible greater than hydrostatic pore pressures developed during dewatering of the clayey sediments (Hubbert and Rubey, 1959). Osmotic pressures caused by the clay acting as a semipermeable membrane (Zen and Hanshaw, 1965) could also have contributed to the development of greater than hydrostatic pore pressures.

A combination of drag folding and gravity sliding probably folded the rocks on the southwest limb of Durmid anticline. Lateral movement of the San Andreas fault initiated drag folding. The drag folding, combined with dewatering and osmotic effects, could have created abnormally high pore pressures within the rocks. As uplift of the Durmid anticline occurred in response to fault movements or intrusive activity, downhill creep of the water-saturated Borrego Formation occurred.

GEOMORPHIC EVIDENCE FOR RECENT TECTONIC ACTIVITY

The relations between landforms and structural features provide a basis for construction of a partial tectonic history of the Durmid area.

Durmid Hill, the largest landform in the area, is low and elongate and is parallel to the northeast side of the Salton Sea (Fig. 2). The hill rises to a height of about 60 m above the Salton Sea and about 15 m above the plain to the northeast. The San Andreas fault roughly follows the crest of the hill. At its south end, Durmid Hill is coincident with the Durmid anticline.

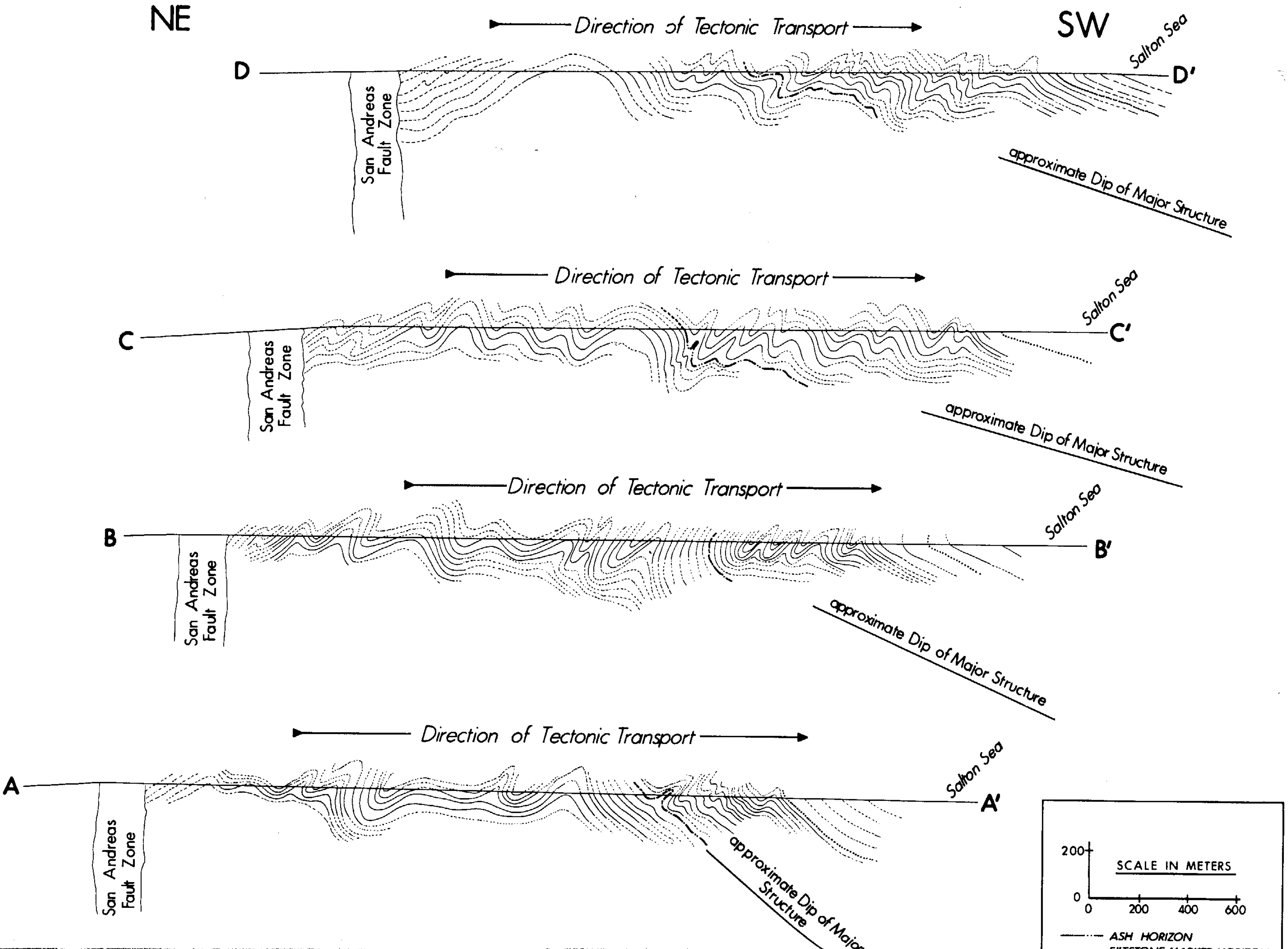
Salt Creek is the major stream in the Durmid area. It heads east of the Chocolate and Orocopia Mountains and drains much of these ranges as well as most of the area between Durmid Hill and the mountains. Where Salt Creek crosses Durmid Hill, it has cut a gorge about 40 m deep (Fig. 9).

Three possibilities might account for the deep canyon cut by Salt Creek. Salt Creek may have captured another drainage network by headward erosion through the hill from the west, or it may be a superimposed stream or an antecedent stream.

It is highly improbable that Salt Creek captured a major drainage system to the east. No geomorphic evidence exists which would indicate that prior to the establishment of the present Salt Creek drainage system, the plain east of Durmid Hill drained in a different direction. In addition, geomorphic evidence (discussed later) shows that the uplift of Durmid Hill was a very recent geologic event. There would not have been sufficient time for a small stream flowing down the southwest side of the hill to erode headward through the hill and capture drainage to the east. Furthermore, none of the other streams draining Durmid Hill has a valley more than 6 m deep or has eroded headward beyond the crest of the hill.

If Salt Creek occupies its present course because of superposition, it would be necessary for the area east of Durmid Hill to have been lowered about 40 m by erosion. No evidence for such an erosional lowering exists. Hence, Salt Creek must be an antecedent stream which has maintained its course during the uplift of Durmid Hill.

The well-developed radial drainage pattern eroded into claystone and siltstone of


NE
SW
Direction of Tectonic Transport
D
D'
Salton Sea
San Andreas Fault Zone
approximate Dip of Major Structure
Direction of Tectonic Transport
C
C'
Salton Sea
San Andreas Fault Zone
approximate Dip of Major Structure
Direction of Tectonic Transport
B
B'
Salton Sea
San Andreas Fault Zone
approximate Dip of Major Structure
Direction of Tectonic Transport
A
A'
Salton Sea
San Andreas Fault Zone
approximate Dip of Major Structure
SCALE IN METERS
200
0
0
200
400
600
ASH HORIZON
SILTSTONE MARKER HORIZON

the Borrego Formation on Durmid Hill, from Bat Caves Buttes to its southern terminus, is an excellent example of consequent drainage. Almost no structural control of drainage is present (except for washes 0.5 m deep or less) in spite of the fact that the bedrock is highly folded and consists of lithologies that have considerable differences in resistance to erosion. The larger washes are 30 to 150 m apart and are generally 1.5 to 3.0 m deep at their deepest point, halfway down the hillside. This youthful drainage system, in which most of the original upland surface is undissected, is interpreted as the initial developmental stage of a drainage system on a smoothly sloping, recently uplifted hill.

Geomorphology provides insight into the geologic and tectonic history of the Durmid area. Folding of the Borrego Formation in response to fault movements probably occurred initially during latest Pleistocene time, forming the Durmid anticline and the small-scale folds associated with it. This was followed by a period of erosion that left the area as a west-sloping plain on which the Salt Creek drainage was established. Renewed upfolding and vertical movement on the San Andreas fault followed, creating Durmid Hill. During this time, Salt Creek maintained its original course and became deeply incised. The presence of Lake Cahuilla silt deposited in small tributary valleys at the Salt Creek canyon indicates that uplift and entrenching of the stream occurred prior to the last high-stand stage of Lake Cahuilla 450 ± 200 yr ago (Hubbs and others, 1965).

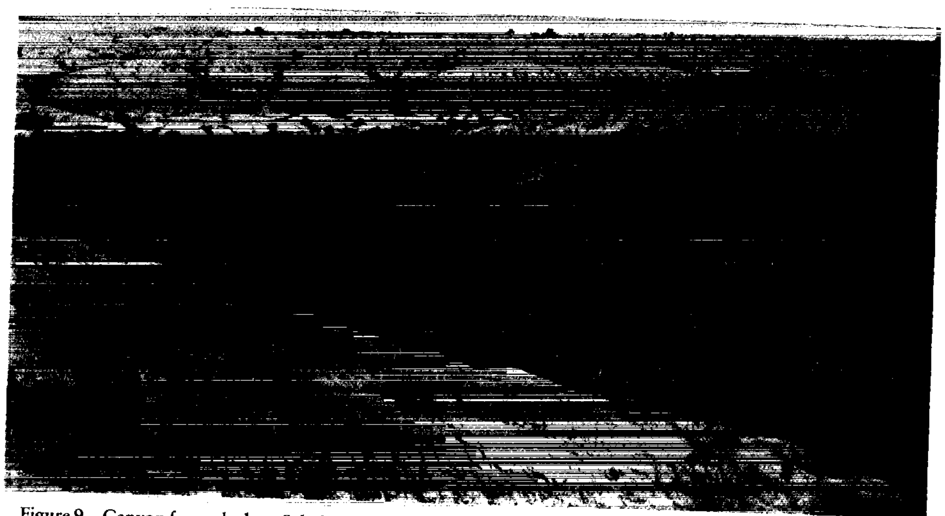


Figure 9. Canyon formed where Salt Creek has cut through the Borrego Formation at Durmid Hill. Deepest portion of the canyon is to the west, behind camera position.

SUMMARY AND CONCLUSIONS

The northeast margin of the Salton trough in the Durmid area consists of a series of subparallel faults belonging to the San Andreas system. Both horizontal and vertical separations were observed across these faults. Structural relief at the Shavers Well-Borrego Formation contact is probably at a maximum at the south end of Bat Caves Buttes. There is a vertical separation of approximately 1,120 m on the San Andreas fault, southwest side downthrown. Folds are present at two scales within the Durmid area: the large-scale Durmid anticline and the small folds on its southwest flank. The timing of events is known only within broad limits because of a lack of accurate paleontological or radiometric dates from rocks in the area.

During late Pliocene or early Pleistocene time, sediments carried into the area were mostly coarse clastics derived from ranges east of the Chocolate and Orocopia Mountains, indicating that these areas were exposed and shedding coarse detritus. Uplift of the Orocopia Mountains near the end of Shavers Well deposition is indicated by clasts of Orocopia schist in the uppermost part of the Shavers Well Formation. Prior to deposition of the Borrego Formation, beds of the Shavers Well Formation were tilted and eroded, creating an unconformity upon which the Borrego lacustrine sediments were deposited. During deposition of the Borrego Formation, the Salton trough probably had a configuration similar to that of today. It underwent repeated periods of dessication, as evidenced by thin evaporite beds of considerable lateral extent. Dessication was interspersed with influxes of mostly clayey and silty sediments, largely derived from the Colorado River (Merriam and Bandy, 1965).

During late Pleistocene time, the Borrego Formation was folded, probably in response to vertical fault movement or intrusive activity along the San Andreas fault zone. This folding formed the Durmid anticline. A tectonically quiet period followed during which the Salt Creek drainage was established and the area was eroded to a smooth surface. The present configuration of Durmid Hill is the result of renewed uplift adjacent to the San Andreas fault in latest Pleistocene time. Salt Creek was offset 850 m right-laterally by movement of the San Andreas fault. The area has been seismically active in recent time, and the author observed small en echelon cracks along the San Andreas fault near Salt Creek following the April 9, 1968, Borrego Valley earthquake. The Durmid anticline may still be rising, and repeated accurate surveying could verify this.

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